Three dimensional finite element simulations of room and pillar mines in rock salt

SAND96-0988C

Edward L. Hoffman and Brian L. Ehgartner
Sandia National Laboratories, Albuquerque, New Mexico, USA

ABSTRACT: Three-dimensional quasistatic finite element codes are being used at Sandia National Laboratories to simulate large room and pillar mines in rock salt. The two examples presented in this paper are of mines supported by the US DOE, under the auspices of the Strategic Petroleum Reserve (SPR) program. One of the mines is presently used as an oil storage facility. These simulations, validated by field measurements and observations, have provided valuable insight into the failure mechanisms of room and pillar mines in rock salt. The calculations provided the basis for further investigation and the ultimate decision to decommission the DOE oil storage facility. Although the simulations were performed in the interest of the DOE's program, these results should be of general interest to mine operators.

1 INTRODUCTION

The US Strategic Petroleum Reserve (SPR) is an oil storage facility created by the United States Department of Energy (DOE) to reduce the vulnerability of the nation to interruptions in foreign oil supply. The SPR currently stores approximately 570 million barrels (MMb) of crude oil in underground caverns in salt domes at five sites located along the Gulf of Mexico. Seventy million barrels of that oil is stored in a room and pillar mine located at Weeks Island, Louisiana which it purchased from Morton Salt Corporation. This mine and a neighboring mine, known as the Markel Mine, have recently begun showing signs of structural instability. This has raised concerns regarding the ability of the facility to adequately isolate the oil reserves from the aquifer overlying the salt dome. An influx of water into the mine could force the stored oil out of the mine, contaminating the aquifer and the above ground environment. Hence, the DOE became interested in performing structural evaluations of its oil storage facility.

The ability to predict the mechanical response of rock salt in three dimensions (3D) to the excavation of a large room and pillar mine would give mine operators the capability of designing mines which were safer and optimized the use of their underground resources. However, room and pillar mines, especially large multi-level mines such as the DOE oil storage facility, typically consist of several hundred pillars. Because each pillar needs sufficient mesh refinement to capture the deformation modes, finite element models of room and pillar mines may require on the order of several hundred thousand elements. Currently available commercial finite element technology does not treat geometric and material non-linearities efficiently enough to handle problems of this size. Because of the solution techniques and constitutive models used in commercial finite element technology, practical limits of around ten thousand elements are typical. As a result, these complex structures are simplified into 2D plane strain models or 3D models of a single pillar. The later pseudo 3D models simulate a mine consisting of an infinite number of rooms and pillars. Neither of these models accurately describe the complex 3D mechanics of a room and pillar mine. However, these were the types of models initially used to certify the DOE facility for oil storage.

Sandia has a long history of research and development in nonlinear large strain finite element codes and the application of these codes to geomechanics problems in waste management programs. Sandia's quasistatic finite element technology is based on iterative solvers and has been extensively developed for large problems involving nonlinear large deformations. The use of iterative solvers and experience with nonlinear material response provides a base technology that offers efficient solution of very large complex geomechanics problems. The DOE storage facility presented an excellent opportunity to apply Sandia technology to the solution of a problem class which was previously not solvable. Much was learned from the use of full 3D models that was not known when 2D models were in use. Although this work was performed to address issues of specific interest to the DOE, these calculations have identified performance issues which should be of general interest to mine operators.

1.1 *History of Weeks Island mining operations*

The DOE oil storage facility is a two-level room and pillar mine which was acquired from Morton Salt Company. Morton mined the upper level (163 m) from 1907 to 1955. Mining of the lower level (224 m) began at this time and continued until the DOE purchased the mine from Morton in 1976. The 1976 purchase agreement allowed Morton to continue utilizing the existing mine shafts for development of an interim mine, known as the Markel Mine, while two shafts were being sunk for the New Morton Mine. The Markel Mine was mined at the same depth as the upper level of the DOE facility and was active until 1981 at which time the new Morton mine shafts were completed and the DOE facility was filled with oil. A plan view of the upper and lower levels of the SPR facility is shown in Figure 1 along with the location of the sinkholes, the Markel Mine, and the New Morton Mine. As the figure shows, the DOE facility contains two types of boundaries: stepped boundaries, where the lower level extends beyond the upper level, and unstepped boundaries, where the extent of the upper and lower levels is the same. Approximately 70 million barrels of crude oil is currently stored at Weeks Island. Morton is presently extracting salt from their Weeks Island facility.

The stratigraphy overlying the salt at the Weeks Island dome, known as the *overburden*, consists of sand and gravel mixed with clay and silt. The ground water regime in these highly permeable sediments is a single aquifer which extends from just below the surface (at sea level) to the top of the salt dome. Domal salt in its natural state is typically considered impermeable. Hence, it provides an excellent barrier between the oil reserves and the overlying groundwater. In the event that a leak developed through the salt into the underground workings, the initial inflow would be saturated. However, if sufficiently high flow rates are established, then flow from less saline

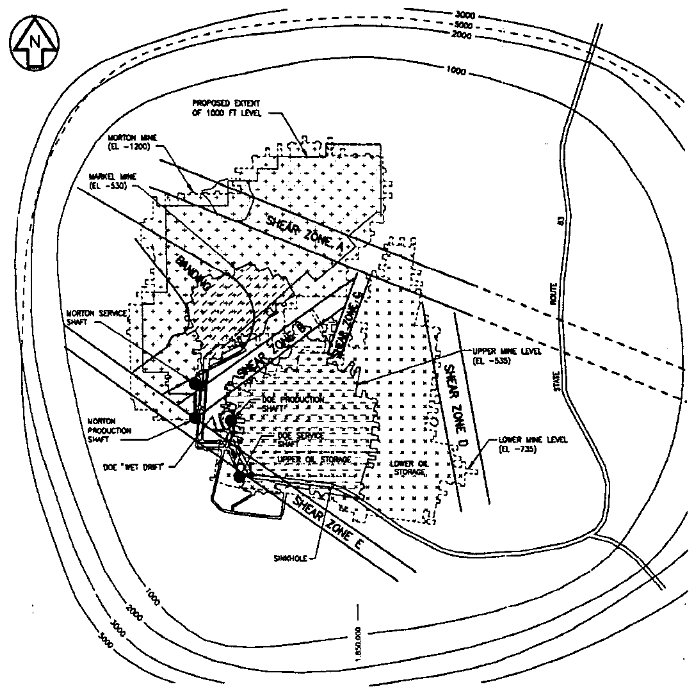

Figure 1. Map of the Weeks Island mines.

portions of the water table could enter the mine causing the solution rate to increase and possibly resulting in a "run away" flooding. A rapid influx of water could force the stored oil out of the mine.

2 GEOMECHANICAL MODELING

2.1 *Structural model*

Gravitational body forces are applied to the model. To ensure initial equilibrium, elevation-dependent initial stresses are applied to each element in the model. The vertical stress component is based on the weight of the overbearing material (using the properties given in Table 1). For the salt, an initial stress state is assumed in which the horizontal stress component is equal to the vertical stress component (lithostatic). For the overburden, the horizontal component is applied to be consistent with a vertically loaded elastic material in equilibrium. Under these load conditions, the resulting ratio of horizontal to vertical stress is defined as $\nu/(1-\nu)$, where ν is the Poisson's ratio of the material.

2.2 *Constitutive model for rock salt*

The sandy overburden is modeled as an elastic material, whereas domal salt exhibits both elastic and creep behavior. The creep constitutive model used for this material considers only secondary creep. The creep strain rate depends on the equivalent deviatoric

Table 1: Structural Properties of Overburden and Salt (WIPP and Bryan Mound)

Material	Elastic Properties		Density, ρ (kg/m^3)	Creep Properties		
	Young's Modulus, E (GPa)	Poisson's Ratio, ν		A ($Pa^{-4.9}/sec$)	n	Activation Energy, Q (kcal/mole)
Salt	31.0	0.250	2300	5.79×10^{-36}	4.90	12.0
Overburden	0.1	0.330	1874	--	--	--

stress as follows:

$$\dot{\varepsilon}^{cr} = A\tilde{\sigma}^n \exp\left(-\frac{Q}{RT}\right) \quad (1)$$

where

$\dot{\varepsilon}^{cr}$ is the creep strain rate,

$\tilde{\sigma}$ is the effective or von Mises stress,

T is absolute temperature,

A and n are constants determined from fitting the model to creep data,

Q is the effective activation energy (cal/mole),

R is the universal gas constant (1.987 cal/mole-K).

The properties used for the overburden and salt are reported in Table 1.

2.3 *Structural stability criteria for rock salt*

In this paper, the structural stability of rock salt is based on two failure criteria for salt: dilatant damage and tensile failure. The dilatant damage criterion, developed from laboratory data on Weeks Island salt (Ehgartner 1994), is used to delineate potential zones of dilatancy in the salt formation surrounding the storage facility. Dilatancy is attributed to microfracturing or changes in the pore structure of the salt, resulting in an increase in permeability and, hence, a flow path for groundwater. The dilatancy surface (Van Sambeek 1993) is defined by a "damage" factor, D, which portrays the potential for dilatant behavior is expressed as $D = \sqrt{J_2}/(0.25\, I_1)$, where J_2 is the second invariant of the deviatoric stress tensor, and I_1 is the first invariant of the stress tensor. When D is equal to or greater than one, the shear stresses in the salt are large compared to the mean stress and dilatant behavior is expected. The region of salt which experiences a change in its pore structure due to the excavation of underground openings has become known as the disturbed rock zone (DRZ).

The measured tensile strength of Weeks Island salt, based on laboratory samples, is approximately 1.07 MPa. For the purposes of these analyses, the tensile strength of Weeks Island salt was assumed to be zero. Tensile cracking in rock salt tends to initiate perpendicular to the largest tensile stress in the rock sample. The largest tensile stress is one of the *principal stresses.* Because the maximum principal stress is the algebraically largest of the three principal stresses (in 3D space) and the largest normal stress in any direction, the potential for tensile failure exists if the maximum principal stress is tensile.

2.4 *Thermal model*

The finite element model includes a depth-dependent temperature gradient which starts at 26.8° C at the surface and increases at the rate of 0.0222° C/m. The temperature distribution is important because the creep response of the salt is temperature dependent. One-way thermal coupling was assumed by entering the thermal data into the structural calculations. This assumption was appropriate since the deformations were not large enough to significantly affect the thermal analysis. Furthermore, mine cooling (due to ventilation and oil fill) is assumed to have a minor effect on salt temperature and consequent deformation rates.

2.5 *Finite element code*

The finite element code JAC3D uses an eight-node hexahedral Lagrangian uniform strain element with hourglass stiffness to control zero energy modes. A nonlinear conjugate gradient method is used to solve the nonlinear system of equations. This efficient solution scheme is considerably faster than the direct solvers which are used in most commercial codes.

3 MARKEL MINE SIMULATIONS

The primary concern regarding the stability of the Markel Mine was the extensive spalling of salt slabs from its pillar walls. Slabs approximately 3 m-thick were reported to have spalled (Acres 1989), yielding an hourglass shaped pillar as shown in Figure 2. The majority of this slabbing occurred in the first few years of operation. Later report indicated that there has been little or no change in the condition of the mine in subsequent years (Acres 1989). The primary concern was what effect, if any, would this spalling have on pillar and mine stability. The principal concern is the potential hydrological impact of the deterioration and possible collapse of the Markel Mine. Flooding of the Markel Mine poses a threat to both the Weeks Island SPR oil reserves and the New Morton Mine. The only barrier between the SPR facility and the Markel Mine are isolation bulkheads which were not designed to isolate the SPR from a flood and may not be strong enough to do so.

While the stability of the Markel Mine has implications on its own, its present condition is of interest since it is at the same depth and utilizes similar extraction ratios as the upper level of the DOE facility. Close monitoring of the condition of the Markel Mine can provide insight as to the condition of the DOE facility which is not as accessible due to oil fill. As the Markel Mine is a relatively small mine, it provided an excellent test case for the numerical tools. Furthermore, the accessibility of the Markel Mine provides a better example for qualitative comparisons with computational simulations.

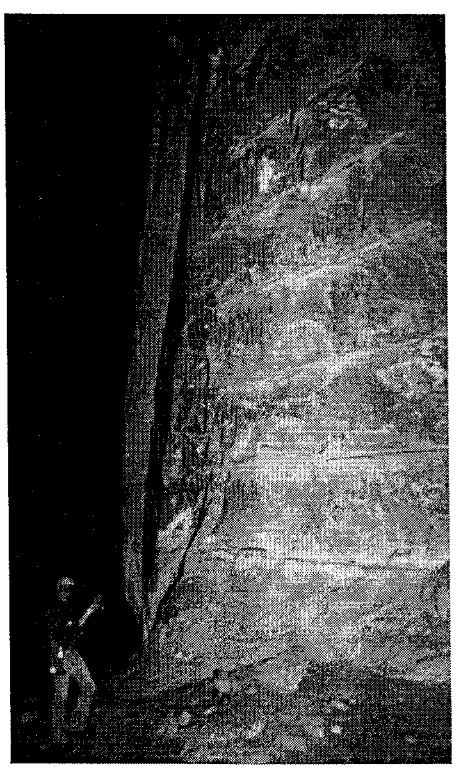

Figure 2. Photograph of a spalling pillar in the Markel Mine.

3.1 *Geomechanical model of the Markel Mine*

The finite element model of the Markel Mine is shown in Figure 3. The model contains 84,968 nodes and 78,720 elements. Although the mine is irregular in shape, it was simplified into a quarter symmetry model approximating the general features of the Markel Mine. This was done in the interest of reducing computational costs, while capturing the relevant parameters of the mine (depth, extraction ratio, etc.). The mine consists of a region of 27.4 m-high rooms called the benched area and a perimeter area of 7.62 m-high rooms called the unbenched area. The roof elevations of the benched and unbenched portions of the mine are the same. The pillars are approximately 29 m square and the rooms are 22.9 m–wide in both the benched and unbenched areas, resulting in an extraction ratio of 0.69. The extraction ratio is defined as the room area, measured in a horizontal plane, divided by the total area (including room and pillar). The model geometry simulates a 45 pillar (5 by 9) mine with an unbenched perimeter. The simulations assume instantaneous formation of the mine which may be appropriate as the Markel was mined in a relatively short period (1.5 years).

Progressive failure was modeled by removing salt from initially square pillars to form hourglass-shaped pillars similar to the observed post-spalled shape of the Markel Mine pillars. Although this model does not simulate the failure mechanisms which lead to spalling, it is useful to determine the post-spalled stress state of the pillars and to evaluate the stability of the pillars after spalling.

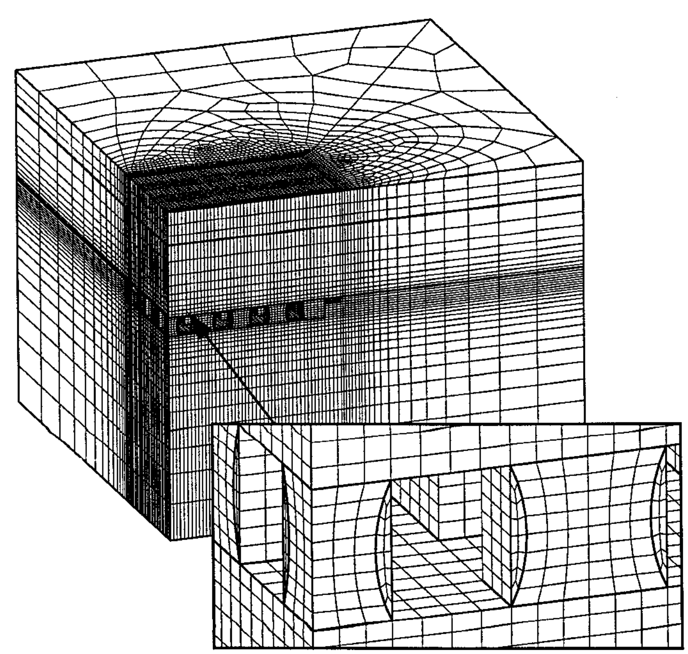

Figure 3. Finite element model of the Markel Mine.

3.2 *Results of the Markel Mine simulations*

Figure 4 shows a contour plot of maximum principal stress in the Markel Mine before spalling, after spalling, and at a time corresponding to the present (analysis time of 18 years). Prior to spalling (2 years into the simulation), a region of tensile stress develops which is approximately 3.05 m thick at the pillar mid-height. After this region of material is spalled off, the stress distribution in the pillar changes such that there are no tensile stresses in the pillar. This is due to the fact that the hourglass shape places the pillar in confinement. Eighteen years into the simulation, the maximum principal stresses in the pillars remain compressive. These results suggest that slabbing is initiated early in the life of the mine by the development of tensile stress in the pillar. The post-spalling shape of the pillar results in the redistribution of stresses such that no further failure will occur as a result of tensile stress, indicating that the mine is stable with respect to this failure mechanism. This would explain why there has been very little slabbing in the Markel Mine since these early failures.

Contour plots of dilatant damage are shown in Figure 5 before spalling, after spalling, and at a time corresponding to the present (analysis time of 18 years). The criterion is plotted only for the salt and not the overburden since the criterion was developed specifically for rock salt. Dilatant damage is indicated where D > 1.0. Before spalling, the DRZ is confined to a small region surrounding the mine. After spalling, the DRZ has increased in size, but the magnitude of damage in the pillars is significantly reduced. Again, this suggests that spalling results in a stress redistribution which is more stable. The spalling results in a slight increase in the damage factor directly above the mine at the overburden/salt interface. However, the damage factor is still less than one. After 18 years, a DRZ begins to appear over one of the mine boundaries at the overburden/salt interface. Furthermore, the DRZ surrounding the mine begins to extend upward at this same boundary. However, the DRZ is small and should not effect the

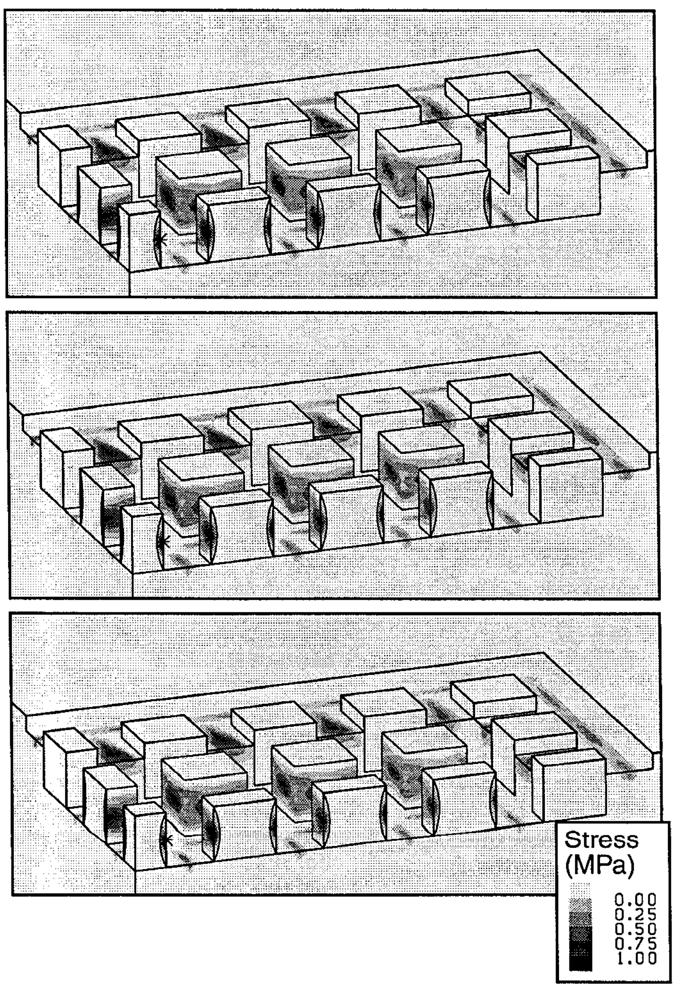

Figure 4. Maximum principal stress distribution in the Markel Mine before spalling, after spalling, and at a time corresponding to the present (t=18 years).

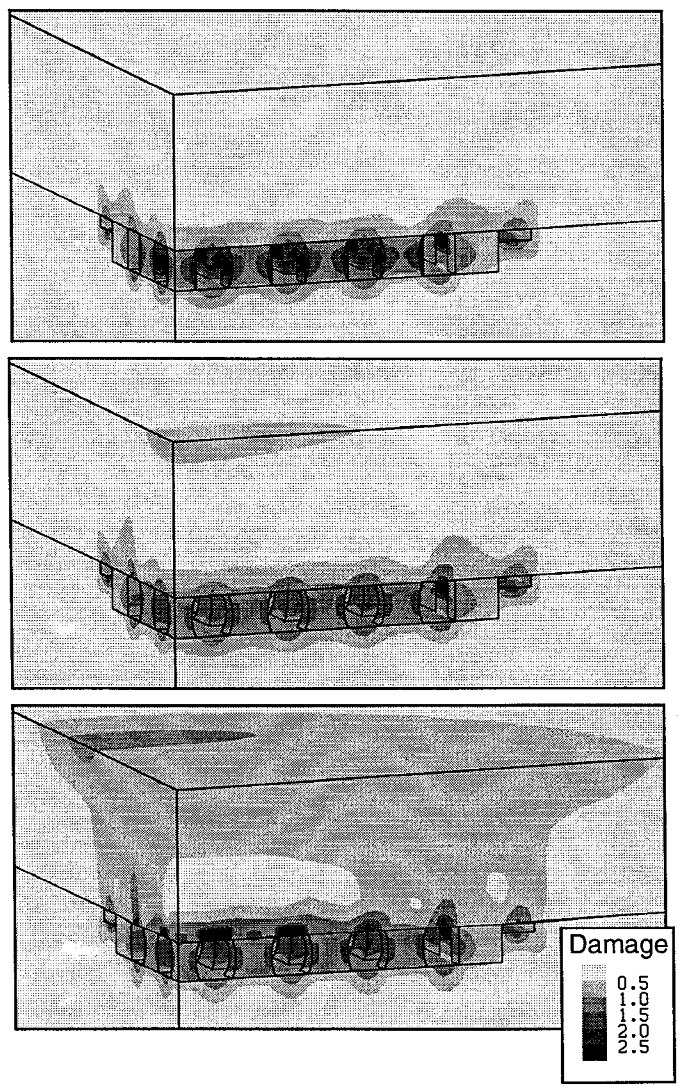

Figure 5. Dilatant damage distribution in the Markel Mine before spalling, after spalling, and at a time corresponding to the present (t=18 years).

hydrological integrity of the mine. These predictions are supported by the fact that, at present, there is no significant influx of water into the Markel Mine.

4 DOE OIL STORAGE FACILITY SIMULATIONS

A sinkhole was recently discovered on southern boundary of the SPR oil storage facility (see Figure 1). The discovery of the sinkhole has raised concerns that the oil reserves may not be adequately isolated from the aquifer located above the salt dome. The following calculations were performed in an attempt to determine the cause of the sinkhole.

4.1 *Geomechanical model of the DOE facility*

As can be seen in Figure 1, the layout of the DOE oil storage facility is irregular, and the pillars and room sizes vary widely. The upper level is at an elevation of 163 m below sea level (measured to the floor of the mine). On average, the pillars are approximately 30.48 m-square and the rooms are 15.24 m-wide, resulting in an extraction ratio of 56 percent. The average room height is approximately 22.9 m throughout most of the upper level. The total capacity of the upper level is estimated to be 35 million barrels (5.56×10^6 m^3). The lower level is at an elevation of 224 m below sea level. The lower level pillars were laid out directly under the upper level pillars for increased support and stability. Hence, the room and pillar dimensions repeat those in the upper level. Like the upper level, the average room height is approximately 22.9 m throughout the lower level except for a small perimeter benched area of 7.62 m high rooms. The total capacity of the lower level is estimated to be 55 million barrels (8.74×10^6 m^3).

In the interest of reducing computational costs, a quarter-symmetry model approximating the general features of the Weeks Island oil storage facility was developed and is shown in Figure 6. The model contains 201,237 nodes and 189,700 elements, representing one of the largest calculations performed with JAC3D to date. The model simulates a 340 pillar mine which is stepped on two opposite sides and unstepped on the other two sides. Displacements are constrained normal to all four vertical boundaries and the lower horizontal boundary.

The calculations simulate the approximate history of the mine, presented in Table 2. The excavation times assume instantaneous formation of the upper and lower levels. In reality, the mines were formed over a long period of time range from 1902 to 1976. Mining of the upper level began in 1902, and was

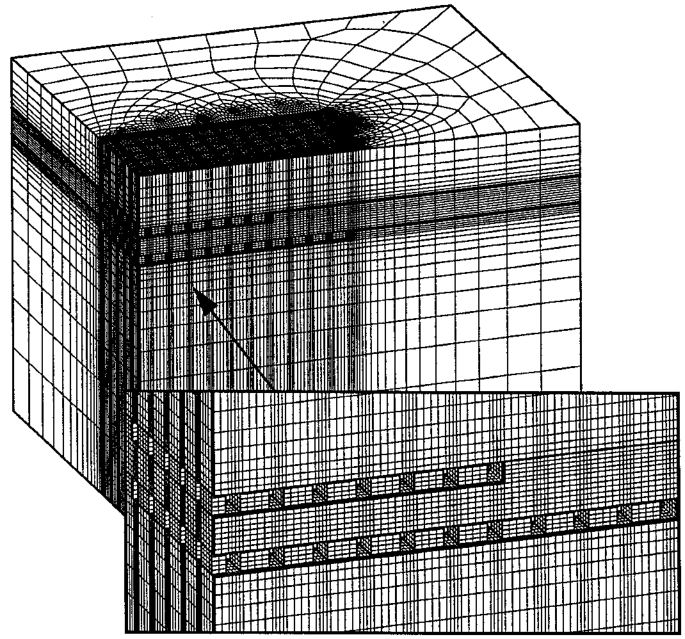

Figure 6. Finite element model of the DOE facility.

completed in 1955. Mining at the lower level began at this time and continued until the DOE purchased the mine from Morton in 1976. The excavation times for instantaneous formation are the average mining dates. The simulation begins with the excavation of the upper level. To simulate the excavation of the lower level, the elements filling the lower level were removed using the element death option in JAC3D (Biffle 1993). Finally, a depth dependent pressure distribution simulating oil storage is applied to the lining of the mine. The calculation was terminated 80 years into the simulation.

4.2 *Results of the DOE facility simulations*

It is desirable, whenever possible, to compare simulations with field data. A comparison of subsidence rate measurements over the DOE facility (Boeing 1992, Jakubik 1992) to the predicted subsidence profile is presented in Figure 7. The subsidence data are corrected such that the farfield subsidence rates are identically zero. The model definition of surface position (*s*) was selected such that it first crosses an unstepped boundary and then the stepped boundary.

Table 2: Model History

Year	Event
1929	Excavate upper level
1967	Excavate lower level
1980	Oil fill
2009	Terminate simulation

This is similar to the path of the field data which starts at the south side of the mine, an unstepped boundary, and moves north, crossing a stepped boundary. The calculations show reasonably good agreement with the field data considering the approximate nature of the model (e.g. instantaneous excavation, pillar spalling not modeled, etc.). Although the magnitude of the subsidence rates differ, the basic shape of the subsidence trough agrees for both the model and field measurements. The extent or width of the subsidence agrees very closely, validating the model prediction that subsidence is localized to within a small range of the mine boundary. Furthermore, the data confirms that the slope of the subsidence contour is steeper where the mine is not stepped, causing a smaller radius of curvature of the subsidence profile and, hence, greater bending of the overlying salt and overburden.

The dilatant damage factor is plotted in Figure 8 for simulation times corresponding to the excavation of the lower level (1967), oil fill (1980), the present (1996), and the year 2008. Like the Markel Mine, a DRZ develops in the walls, floor and ceiling of the mine. However, unlike the Markel simulations, the DOE simulations predict the development of a DRZ initiating at the salt/overburden interface, directly over the unstepped boundary. This DRZ initiates when the lower level of the mine is excavated. The DRZ grows with time, extending toward the corner of the mine. At present, the DRZ is predicted to have progressed more than half-way through the salt roof. By the year 2008, the DRZ has grown even larger and is within 25 m of the DRZ developing around the mine. The DRZ is largest over the unstepped boundary due to the greater bending at this location, indicated by the steeper subsidence trough over this boundary (see Figure 7). This corresponds to the location where the sinkhole developed. Hence, the development of the sinkhole is indicative that the DRZ may have connected the mine to the overlying aquifer. It should be noted that, because the sinkhole developed along the boundary of the facility, this mode of mine failure could only be identified with a full 3D model of the mine, including both stepped and unstepped boundaries.

The predicted DRZ may have been encountered in

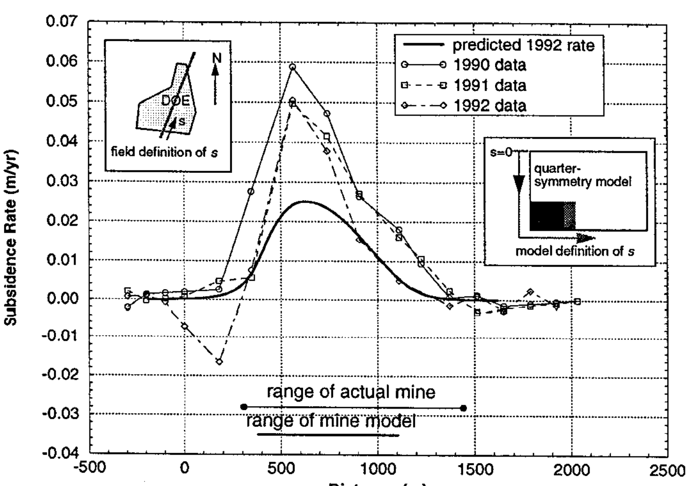

Figure 7. Comparison of predicted subsidence rates (corresponding to 1992) to Weeks Island data.

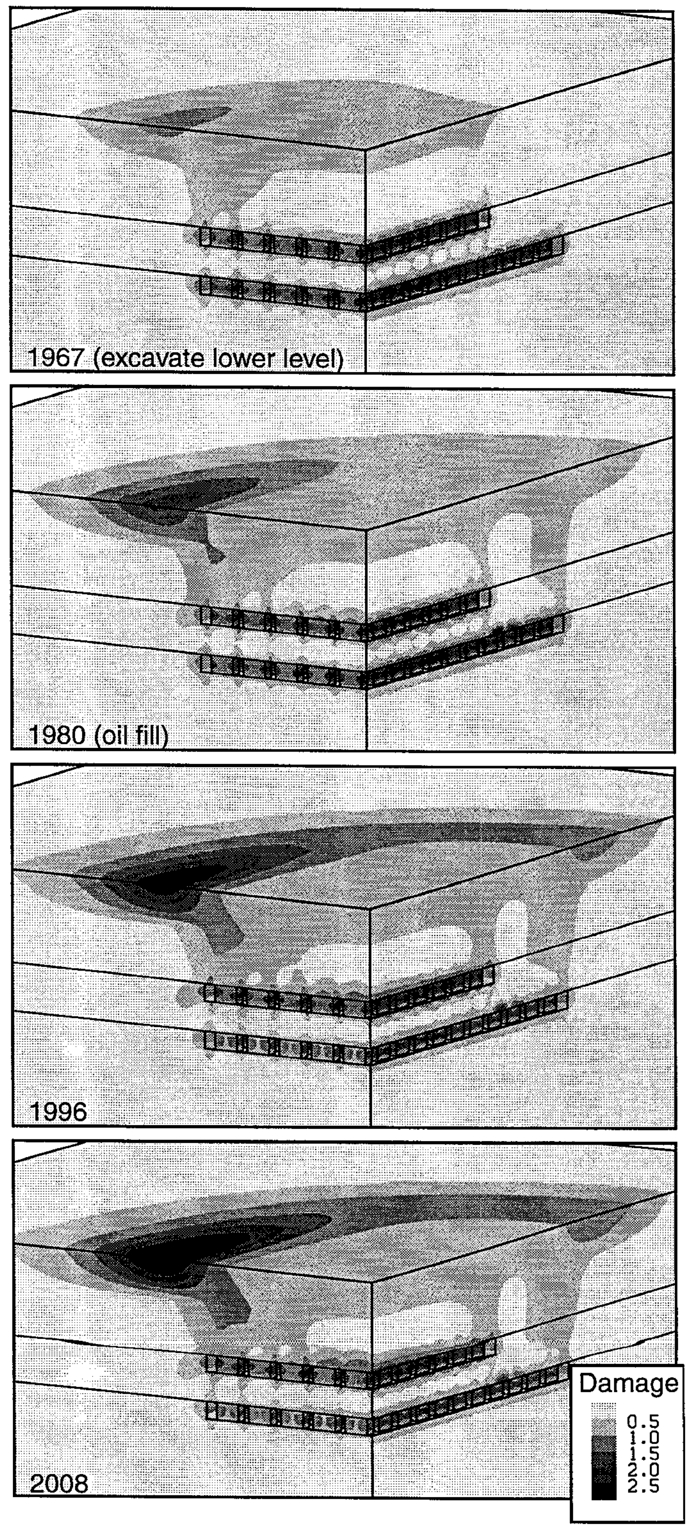

Figure 8. Dilatant damage distribution around the DOE oil storage facility.

1977 while mining a drift to the Markel area. A zone of wet salt was encountered during routine drilling and blasting. Mining was halted and, after significant brine inflows, a bulkhead was installed at the entrance of the drift. Since neither the Markel Mine nor the New Morton Mine had yet been developed in 1977, the wet salt may be attributed to dilatant damage caused by the DOE oil storage facility. The "wet drift" (as labeled in Figure 1) is located along one of the unstepped boundaries of the DOE facility and leaks to this day despite repeated grouting attempts to stop inflow.

5 SUMMARY AND CONCLUSIONS

Two complex room and pillar mines were analyzed with JAC3D, a three-dimensional quasistatic finite element code developed at Sandia National Laboratories. The iterative methods and reduced integration techniques used in JAC3D are considerably faster and use significantly less memory than the direct solvers used in most commercial finite element code. The economical solution of these problems indicates that iterative techniques are powerful tools for the analysis of large multi-level mines. In fact, these may be the only tools capable of solving problems of this size.

These simulations, validated by field measurements and observations, have provided better insight into the failure mechanisms of room and pillar mines in rock salt. Pillar spalling was commonly thought to be a degenerative process which would progress until the pillar ultimately failed. The pillar spalling simulations identified tensile failure as the probable cause of pillar spalling. The calculations demonstrate that spalling produces a pillar shape which has a more stable stress distribution. Most importantly, the calculations demonstrate that the spalling process has no observed effect on the overall stability or hydrological integrity of the mine. The simulations of the DOE oil storage facility identified a failure mechanism which may have lead to the development of a sinkhole over the boundary of the facility. These calculations also demonstrate the size of the DRZ is dependent upon the geometrical configuration of the mine. The DRZ did not develop until the lower level of the mine was excavated. Furthermore, the magnitude and extent of the DRZ was significantly larger over the unstepped boundaries. These calculations provided the basis for further investigation and the ultimate decision to decommission the Weeks Island DOE oil storage facility. Although the simulations were performed in the interest of the DOE's SPR program, these results should be of general interest to mine operators.

Acknowledgements—This work was supported by the United States Department of Energy (DOE) under contract No. DE-AC04-76DP00789.

REFERENCES

Acres International Corporation 1989. *Report on Markel Mine Inspection.*

Biffle, J.H. 1992. *JAC3D - A Three-Dimensional Finite Element Computer Program for the Nonlinear Quasistatic Response of Solids with the Conjugate Gradient Method* SAND87-1305. Sandia National Laboratories, Albq., NM.

Boeing Petroleum Services, Inc. 1992. *SPR Annual Subsidence Report*, Pub. No. D506-03165.

Ehgartner, B.L. 1994. Dilatancy Criterion for Weeks Island Salt. Internal Sandia Memorandum to J. K. Linn. Sandia National Laboratories, Albq., NM.

Jakubik, J.T. 1992. *Dec '92 Survey of Weeks Island*, letter to Boeing Petroleum Services.

Van Sambeek, L.L., J.L. Ratigan, & F.D. Hansen 1993. Dilatancy of Rock Salt in Laboratory Tests. *Proc. 34th U.S. Symposium on Rock Mechanics.*